Limnological Evaluation of a Sockeye Salmon Stocking Program in Solf Lake

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Product names used in this report are included for scientific completeness, but do not constitute product endorsement by the Alaska Department of Fish and Game.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

In 1998, a sockeye salmon (*Oncorhynchus nerka*) fry stocking program was initiated in Solf Lake. This program was developed as a means to replace damaged resources and benefit subsistence users in western Prince William Sound (Chenega Bay and Tatitlek) who may have lost harvest opportunities as a result of the T/V *Exxon Valdez* oil spill, and to reestablish a sustainable sockeye salmon run. Prior to an earthquake in the 1930's that made the outlet impassable to anadromous fish, a sockeye salmon run existed in Solf Lake. Solf Lake is classified as oligotrophic based on very low total phosphorus and chlorophyll *a* concentrations and high water clarity and light penetration. Nutrient concentrations were all below mean values derived for 57 Alaskan clear lakes that support juvenile sockeye salmon. In addition, Solf Lake has a short growing season of 133 days, and the onset of spring heating is about a month later than other Alaskan nursery lakes. Surface water temperatures (1 m) were cold at the time of stocking, 7° C in 1998 and 2000, and 4° C in 1999, which could have limited fry growth and increased mortality. The macrozooplankton community of Solf Lake is composed mainly of the copepod *Diaptomus kenai*, a rare morph exhibiting a red pigmentation visible to the naked eye. Populations of pigmented *Diaptomus* have been documented in only two other Alaskan lakes. Although mean length of Cyclops, another copepod, and Bosmina, a cladoceran, were smaller during stocking than before stocking, there was no difference in density or biomass between pre-stocking and during stocking. The sockeye salmon fry stocking density in Solf Lake was low (0.19 m^{-2}) compared to other barren lakes in Alaska that have been stocked (mean 0.51 m^{-2}). After stocking in 1998, only 248 sockeye salmon smolt were enumerated in 1999. However, smolts were large and robust, with a mean size of 134.7 mm and 22.9 g. Based on the 1999 smolt enumeration program and the September 1999, mid-June, and mid-July 2000 hydroacoustic surveys that showed very few fish rearing in the lake, sockeye salmon fry appear to have either emigrated from the lake or died shortly after planting. We believe the fry emigrated as age-0 smolt, but were probably unable to survive as they would have reared in the lake for less than one month during 2000. Therefore, we recommend delaying stocking for two weeks later than previous stockings, holding the fry in net pens near an inlet stream for a week before release, or stocking the lake in late fall with fry.

INTRODUCTION

The Solf Lake sockeye salmon (*Oncorhynchus nerka*) stocking program was developed by the Alaska Department of Fish and Game (ADF&G), Division of Commercial Fisheries (CF), U.S. Forest Service (USFS), and *Exxon Valdez* Oil Spill (EVOS) Trustee Council as a result of the T/V *Exxon Valdez* oil spill. The primary goals were to develop a sustainable sockeye salmon run and to benefit subsistence users in western Prince William Sound (Chenega Bay and Tatitlek) who may have lost harvest opportunities.

The stocking of barren lakes with sockeye salmon fry is done for numerous reasons: 1) to take advantage of under-utilized habitat (rearing capacity), or develop a new run (Blackett 1987; Bechtol and Dudiak 1988; Edmundson et al. 1993; Kyle 1994), 2) to provide increased fishing opportunities for commercial, sport, and subsistence users by supplementing local stocks, and 3) to examine nutrient-trophic interactions in response to changing fish densities. The latter has been used to understand the sockeye salmon carrying capacity of lakes and develop mechanistic models relating limnological variables to smolt and adult biomass (Koenings et al. 1989; Edmundson et al. 1993; Budy et al. 1994; Kyle 1994; Kyle et al. 1997). Stocking of barren lakes in Alaska has produced mixed results (Kyle 1996). For example, Leisure Lake (Kyle 1996), a small lake on the Kenai Peninsula, and Spiridon Lake (Honnold 1997), a large lake on Kodiak Island, now support viable, economically important commercial and personal use fisheries. However, Edmundson et al. (1993) demonstrated that stocking exceeded the carrying capacity of Pass Lake in Prince William Sound. Even when stocking was discontinued and the lake fertilized with inorganic nutrients, the zooplankton community did not recover sufficiently to warrant further enhancement. We would expect to see a reduction in zooplankton biomass, density, and size from grazing by fry when a barren lake is stocked. Thus, it is necessary to balance fry densities with available forage to have a successful stocking program.

Objectives

Our objectives in the Solf Lake stocking program were to: 1) monitor limnological conditions related to sockeye salmon fry growth and survival, 2) assess growth and survival of fry, and 3) determine the abundance, size, condition, and timing of emigrating sockeye salmon smolt. Physical conditions, water chemistry, nutrient concentrations, and zooplankton abundance were monitored monthly to assess impacts of stocking. This information is critical because the stocking of juveniles beyond a lake's carrying capacity may not achieve our desired goal of producing a large number of healthy smolts.

Study Site Description

Solf Lake (60° 26′ N, 147° 42′ W) is located on the northeast side of Knight Island, and drains into Herring Bay in Prince William Sound, Alaska (Figure 1). The topography bordering Prince William Sound is in the northern coastal rain forest and receives large amounts of precipitation,
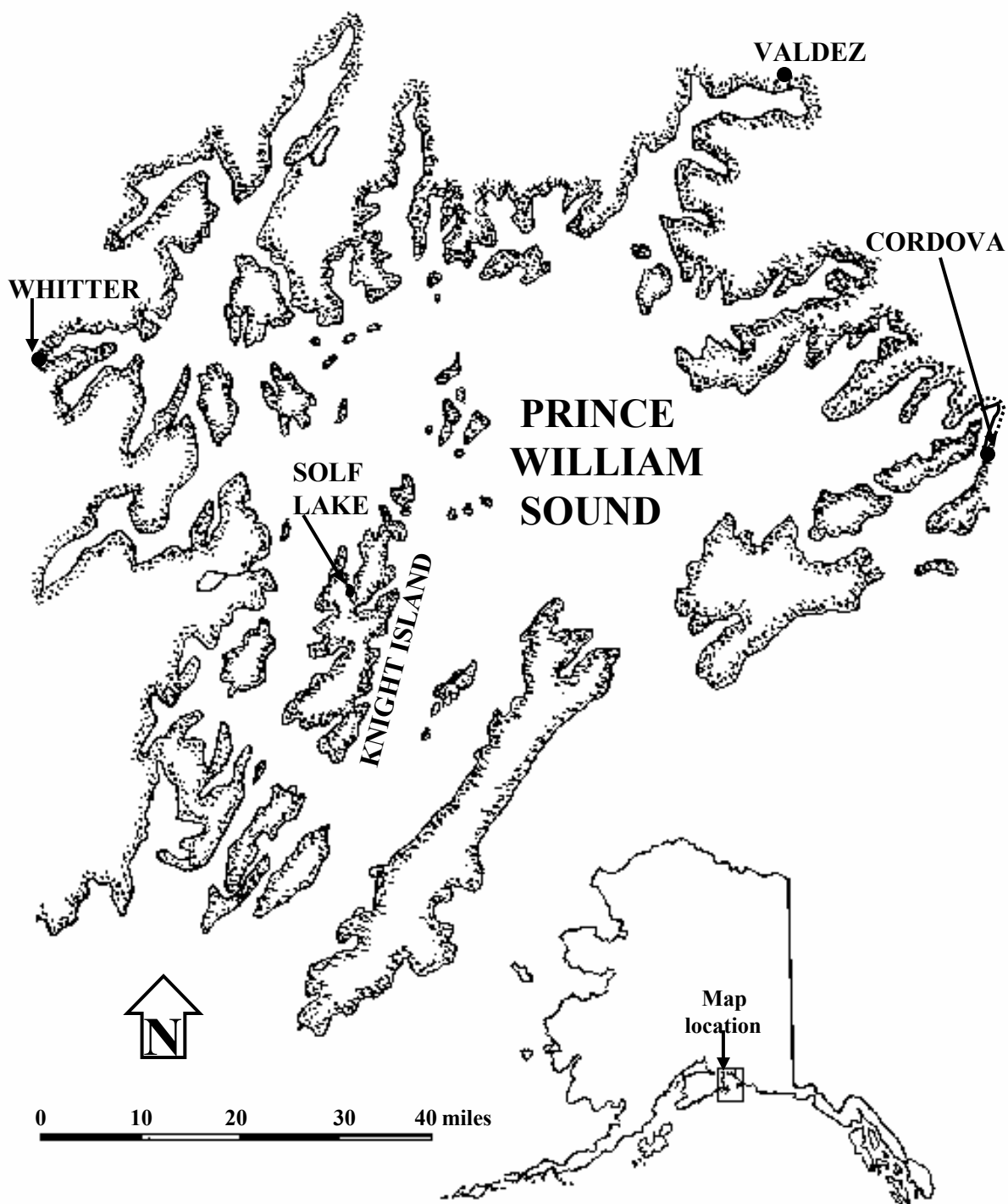
Figure 1. Geographic location of Solf Lake in Prince William Sound, Alaska.

as both rain and snow. Solf Lake is at an elevation of 8 m and has two outlets; one over a man made diversion dam to allow water flow through a second narrow canyon outlet. The canyon is less than 100 m long and the U.S. Forest Service (USFS) channeled the stream and installed fish passes to allow anadromous fish passage into the lake. There are five small creeks entering the lake, three of which are probably seasonal. The lake has a surface area of 0.6 km^2, a maximum length of 1.8 km, a mean depth of 42.5 m, a maximum depth of 96.0 m, and volume of 25.8 x 10^6 m^3 (Figure 2). For a relatively small lake, the basin characteristics are favorable for rearing sockeye salmon juveniles because the lake is steep sided as indicated by the depth-volume plot (Figure 3a). Approximately 50% of the lake volume is contained in the upper 30 m. The depth-area plot (Figure 3b) shows the lake to have a small littoral area. Prior to an earthquake in the 1930's that made the outlet impassable to anadromous fish (Nickerson 1978), a sockeye salmon run existed in Solf Lake. Since then, this lake was considered barren (Pellissier and Somerville 1987), although later fishery assessments documented a few Dolly varden (*Salvelinus malma*).

Fry Stocking

Solf Lake has been stocked with sockeye salmon fry annually since 1998. Eyak Lake stock fry were planted in 1998 and Coghill Lake stock fry were stocked for all other years. Because of the spatial separation of Solf Lake from other wild sockeye salmon systems (stocks) in Prince William Sound, adverse genetic impacts from straying were thought to be minimal (Seeb 2000). All eggs were incubated and fry reared at the Main Bay hatchery, in Prince William Sound, Alaska. Fry were transported by aircraft (on floats) to the lake and released in the southern half of the lake, away from the outlets. Transport flights from Main Bay Hatchery to Solf Lake took approximately 12 minutes. On 25 May 1998, a total of 109,827 fry were stocked at a mean fry weight of 0.51 g. The mean number and size of stocked fry was 112,064 and 0.47 g (Table 1). In 2001, the fry were held in a net pen for 3 days near an inlet creek along the south shore of the lake before release. Upon release from the pen, USFS personnel observed fry swimming erratically and dead fry were found in the bottom of the pen. They estimated 5,000 fry (4%), died during holding.

METHODS

Limnology Assessment

During 1996 and 1998-2000, we conducted limnological sampling approximately once a month (June-September) at one site in the middle of the lake, and collected additional zooplankton samples from a second site (Table 2, Figure 2). Previous limnological data from one station, collected in 1982-1984 and 1986 are also included in this report, but have also been reported elsewhere (Barto and Nelson 1982, Pellissier and Somerville 1987).

We collected water samples for nutrient and general water-quality tests from 1 and 50 meter depths using an 8-L Van Dorn sampler. Water samples were returned to the ADF&G limnology

SOLF LAKE
Latitude: 60° 26'
Longitude: 147° 42'
Elevation: 8 m
Area: 0.6 x 10^6 m^2
Mean Depth: 42.5 m
Maximum Depth: 96.0 m
Volume: 25.8 x 10^6 m^3
Contours in meters
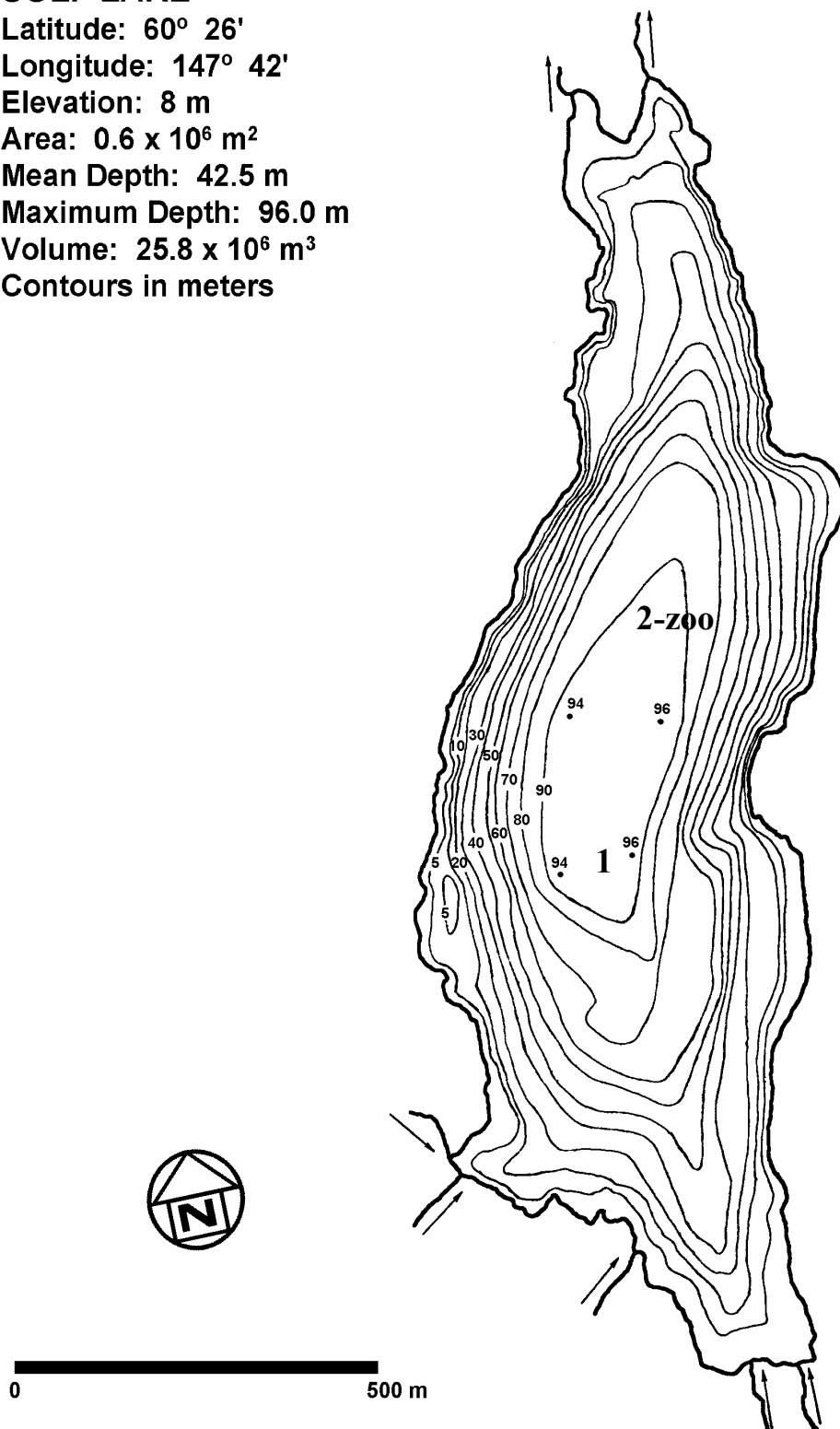
Figure 2. Bathymetric map of Solf Lake showing locations of the limnology sampling stations.
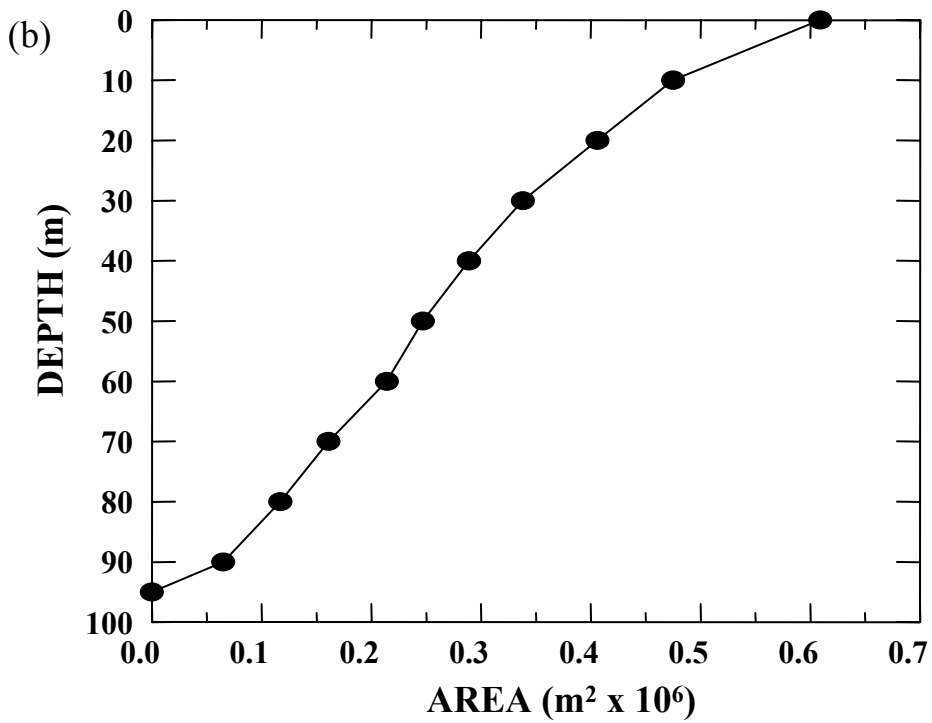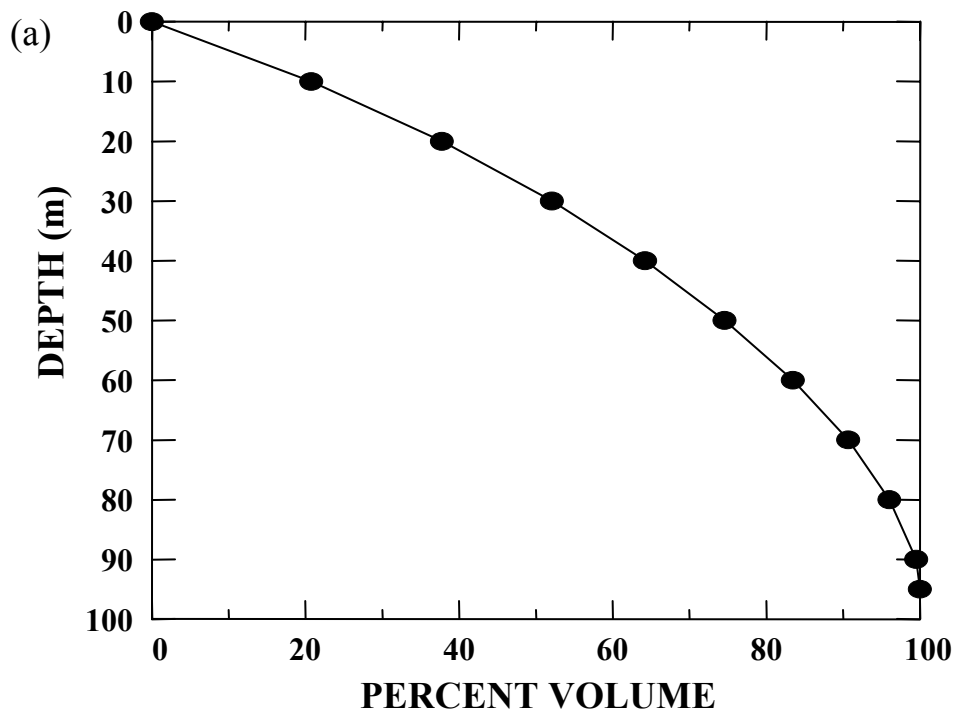
Figure 3. Depth-volume (a) and depth-area (b) plots for Solf Lake.

Table 1. Summary of sockeye salmon fry stocking in Solf Lake, Alaska

Year	Stocking date(s)	Number trips	Number stocked	Size (g)	Broodstock	Hatchery	Marks
1998	25-May	2	109,827	0.51	Eyak Lake	Main Bay	3,193 CWT
1999	18-Jun	2	105,829	0.41	Coghill Lake	Main Bay	2,687 CWT
2000	15-Jun	1	116,500	0.42	Coghill Lake	Main Bay	100% Otolith
2001	15-Jun	2	116,100	0.53	Coghill Lake	Main Bay	100% Otolith
Mean			112,064	0.47			

Table 2. Solf Lake limnology sampling, years and dates.

Year	Number trips	stations [a]	Sampling dates					
1982	4	1	1 Mar	16 Jun		5 Aug		6 Nov
1983	6	1		11 Jun	14 Jul	27 Aug	30 Sep	19 Oct, 1 Nov
1984	5	1	24 May	16 Jun	7 Jul	9 Aug	12 Sep	
1986	4	1		11 Jun	1 Jul	1 Aug	2 Sep	
1996	1	1		6 Jun				
	4	2			3 Jul & 19 Aug		23 Sep	
1998	4	2		13 Jun	28 Jul	26 Aug	24 Sep	
1999	5	2		16 & 28 Jun	29 Jul	25 Aug	28 Sep	
2000	4	2		16 Jun	19 Jul	18 Aug	30 Sep	

[a] All limnology sampling was done at one station, and the second station was an additional zooplankton tow only.

laboratory in Soldotna where they were processed using standardized methods (Koenings et al. 1987). Water for dissolved nutrients (nitrogen and phosphorus), color, and chlorophyll *a* (chl *a*) were filtered (1-L each) through Whatman GFF (glass-fiber) filters. Water samples were stored for later analysis (filtered and unfiltered, frozen and refrigerated) in cleaned (phosphate free soap washed and deionized water rinsed) polyethylene (poly) bottles. Tests conducted on filtered, frozen water samples included filterable reactive phosphorus (FRP) or soluble orthophosphate, total filterable phosphorus (TFP), nitrate + nitrite, total ammonia, and color. FRP was analyzed by the molybdenum blue/ascorbic acid reduction procedure as modified by Eisenreich et al. (1975). Nitrate + nitrite was analyzed as nitrite following cadmium reduction as adapted from Stainton et al. (1977). Total ammonia utilized the phenylhypochlorite methodology. Color was determined from a filtered sample, by measuring the spectrophotometric absorbance at 400 nm and converting to equivalent platinum cobalt (Pt) units (Koenings et al. 1987). Tests on unfiltered (frozen) water included total phosphorus (TP) and total Kjeldahl nitrogen (TKN). TP analysis utilized the FRP procedure after acid-persulfate digestion (Eisenreich et al. 1975). TKN was determined as ammonia following acid-block digestion (Technicon Industrial Systems 1978). Total nitrogen (TN) was computed as the sum of TKN and nitrate + nitrite.

A sample of unfiltered water was also refrigerated for analysis of general water chemistry tests: conductivity, pH, alkalinity, turbidity, calcium and magnesium, iron, and reactive silicon. Conductivity (temperature compensated to 25° C) was measured using an YSI conductance meter, and pH was measured with an Orion model 420A pH meter (APHA 1985). Alkalinity was determined by acid (0.02 N H_2SO_4) titration to pH 4.5 units (APHA 1985). Turbidity, expressed as nephelometric turbidity units (NTU) was measured with a HF model 00B meter (APHA 1985). Calcium and magnesium were determined from separate EDTA (0.01 N) titrations (Golterman 1969). Total iron was analyzed by reduction of ferric iron with hydroxylamine during hydrochloric acid digestion as modified from Skougstand et al. (1979). Reactive silicon was determined using the method of ascorbic acid reduction to molybdenum blue procedure by Technicon Industrial Systems (1977).

Chl-*a* samples were treated with ~2 ml of $MgCO_3$ prior to completion of filtering. The filters were placed into individual Petri slide filter holders and stored frozen until analyzed by laboratory personnel. We extracted algal pigments by grinding the filters with a Teflon pestle in 90% acetone and refrigerating the slurry at 4° C in the dark for 2 h. After acetone extraction, the slurry was centrifuged and the supernatant was decanted and brought to volume with 90% acetone. The chl *a* concentration (corrected for inactive phaeophytin) was determined as modified from Strickland and Parsons (1972) using a calibrated (Sigma Co. chl *a* standards) Turner model 112 fluorometer.

We recorded climatic conditions (wind speed and direction, percent cloud cover or haze, and precipitation) at the time of sampling. We measured underwater irradiance with either a Li-Cor or an International Light submarine photometer. Both photometers were equipped with a cosine corrected sensor, which measured PAR (photosynthetically active radiation, 400-700 nm). Vertical light extinction coefficients (K_d), the rate (m^{-1}) of underwater light decay, and euphotic zone depth (EZD) were calculated according to standard methods (e.g., *see* Wetzel and Likens 1991). EZD is defined here as the depth to which 1% of the subsurface light (PAR) penetrates, or the estimated maximum depth of net primary production (Schindler 1971). Vertical profiles

of temperature and dissolved oxygen (DO mg L^{-1}) were measured from the surface to 5 m at 1 m intervals and at 5 m intervals from 5 m to 50 m using a Yellow Spring Incorporated dissolved oxygen/temperature meter. The oxygen sensor was calibrated with a Hach kit using the Winkler titration method (APHA 1985). During 2000, we measured temperature, DO, and conductivity with a Hydrolab instrument with an internal depth sensor. Measurements were recorded at the same depths as prior years, and below 50 m at 10 m intervals to the bottom. Water clarity was measured with a 20 cm Secchi disk (SD).

Zooplankton Assessment

We collected zooplankton samples by towing vertically from a depth of 50 m to the surface, using a 0.2 m diameter; 153 μm mesh conical net, with attached collection cup. Samples were preserved in a 10% buffered formalin solution. A binocular dissecting microscope was used for zooplankton identification, enumeration and length measurements. A 1.0 ml subsample was taken with a Hansen-Stemple pipette and placed onto a Sedgewick-Rafter counting cell, and all organisms in five 0.01 cm^2 grids were counted. Three replicates were counted for each sample. We measured body length to 0.01 mm from 10 individuals along a transect in each subsample, as described in Koenings et al. (1987). Computations of biomass also followed procedures from Koenings et al. (1987) using species-specific regression equations relating mean wet length to dry mass. We calculated the density and biomass by species, for comparisons of pre-stocking and during-stocking variations. Zooplankton density and biomass are expressed on an areal basis (Nr. m^{-2} and mg m^{-2}). Zooplankton were sampled at two sites beginning on the second trip in 1996. To compare zooplankton densities and biomass prior to stocking to during-stocking, we used only the data for station 1, as this station was sampled consistently all years.

Fisheries Assessment

Smolt Enumeration and Sampling

On 2 May 1999, we installed a live-box at the flow control structure at the northwest outlet to enumerate and sample emigrating sockeye salmon smolt. We placed fine mesh netting (5 mm) in front of the northeast outlet to force the smolt through the live-box and to keep fry and smolt from emigrating over the waterfall. On 16 June, we replaced the live-box with an inclined-plane trap (Todd 1994) with attached live-box placed in front of the flow control structure. Perforated aluminum plate placed between the trap openings and shore maintained a total capture of emigrating fish. On 26 June, the trap was removed for the season. We monitored the live-box periodically throughout the day and late evening to avoid overcrowding and subsequent smolt mortality. The smolt enumeration-sampling program was discontinued after the 1999 season.

All captured smolt were enumerated and released downstream, and size and age data were collected from a subsample. We anesthetized the sampled smolt in a solution of MS-222 (methanesulfonate) and measured fork length (FL, mm). We obtained weights to 0.1 g using an electronic scale. To determine age, we took a scale smear from the primary growth area, which

was then placed on a labeled glass slide. The scales were analyzed with a microfiche scale reader (Tobias et al. 1994).

Hydroacoustic-Townet Surveys

On the night of 27 September 1999, we conducted a hydroacoustic and tow net survey to estimate the number and distribution of rearing sockeye salmon juveniles from the 1998 and 1999 spring stockings. We conducted the survey at night because juvenile sockeye salmon are typically more dispersed during darkness and easily detected by hydroacoustic equipment. We ran transects at approximately 1.5 m s^{-1}, and monitored our speed with a Marsh McBirney model-201M flow meter attached to the hydroacoustic V-fin tow body. Transect course was maintained with a lighted Ritche compass mounted on the starboard gunwale of the boat. Down-looking acoustic data was recorded along 12 randomly selected transects, perpendicular to the longitudinal axis of the lake. A BioSonics model-105 echo sounder system with a 6/15° dual-beam, 420 kHz transducer, mounted in a BioSonics V-fin tow body was used for the survey. Fish signals or targets were recorded electronically using a Sony digital audio tape recording system and on paper using a BioSonics model-115 chart recorder. ADF&G CF personnel at Soldotna, Alaska analyzed the recorded hydroacoustic tape. We conducted tow netting in conjunction with the hydroacoustic survey to collect samples of rearing fish for size and growth studies. A 2 × 2 m monofilament tow net was towed at 0.5-1.5 m s^{-1} by one boat at 15 m depth (suspended by buoys and measured lines), along the longitudinal lake axis. Approximately ¾ the total lake length was towed.

In 2000, we conducted two hydroacoustic surveys. The first survey was conducted before the lake was stocked with fry to count fry/smolt remaining in the system from previous year's stocking. We ran 11 transects during the night of 15 June, all perpendicular to the longitudinal lake axis. On the second survey, the night of 19 July, 13 perpendicular transects were run down-looking, and side-looking was conducted from mid-lake to the north end with the transducer at 2 m depth. We conducted the second survey to estimate fry survival and distribution after the 2000 spring stocking. Both surveys were preformed using a BioSonics DT-6000 scientific echosounder, attached to a Dell Inspiron laptop computer via a PCMICA data connection cable. We used BioSonics Visual Acquisition program for all data collection, and input of the collection parameters into the program were done prior to the surveys: data threshold –65 decibels (dB), 3 pings s^{-1} ping rate, and 0.2 milliseconds pulse width. A BioSonics 6.6^o circular diameter, 200 kHz split-beam digital transducer was attached to a 1.5 m aluminum tow-sled for both surveys. We suspended the tow-sled at 1 m depth, from a boom placed off the bow of the boat. A Garmin model-175 global positioning system (GPS) receiver was used to maintain transect course and speed (2-2.5 m s^{-1}). Bob DeCino of ADF&G CF, Soldotna, analyzed both surveys using BioSonics Visual Analyzer program. We did not tow net with either hydroacoustic survey in 2000.

Statistical Analysis

We used one-way ANOVA to test for differences before and during stocking in zooplankton density, biomass, and size. All statistical tests were conducted using SYSTAT version 9 (SPSS 1998) and a significance level of $\alpha = 5\%$. Seasonal means were calculated as the mean of all corresponding values for one season and one depth. Light penetration measurements used to calculate EZD and K_d followed the methods in Edmundson et al. (2000). Temperature parameters were calculated after Edmundson and Mazumder (2002). The projected day of year when temperature reaches 4° C (isothermy) in the spring represents the start of the growing season (H_i), and fall isothermy marked the end of the growing season (H_f). The duration of the growing season (S) was calculated as the difference between H_f and H_i. The date of maximum heat content (H_m) was the projected day of maximum water temperature (T_{max}) for the 1 m stratum. To compute the Birgean summer heat budget, we calculated the average temperature for different depth stratums at the time of H_m, which incorporates the change in volume with depth (Wetzel and Likens 2000). All strata were summed to give the total lake heat content ($V T_s$) in calories. We divided the heat content by the surface area of the lake (k-cal cm^{-2}) to express the heat budget by per-unit-area. The difference in heat content between H_i and H_m is the summer heat budget (θ_s).

RESULTS

Limnology Assessment

Physical Environment

The lake begins to heat above 4° C around mid-June, peaks in early August, and cools to 4° C by late September. In 1999 the 1 m water depth temperature was 3° C colder in the spring (mid-June) than other measured years, and was probably a result of the late spring and heavy snow pack during the 1998-1999 winter. Over the years sampled, maximum surface temperatures ranged from 11 to 18° C, with 1996 considerably warmer than the other years and over 3° C warmer at peak temperature H_m (Figure 4a). However, by late September the temperatures were similar for years 1996 and 1998-2000 (Figure 4b). Although the 5 m temperatures were within a degree of the optimum temperature for growth during 1998-2000, temperatures at 10 m ($\sim 6^o$ C) and deeper were much colder (Figure 4a). The lake thermally stratifies for brief time periods as shown by vertical water temperature profiles (Figure 4a) but a persistent thermocline did not exist. In August 1996, there was a 5.9^o C difference between 2 and 3 m, and during both July and August 1998, the lake was stratified between 4 and 5 m. However, the lake did not undergo thermal stratification in the summer of 2000, but instead temperatures decreased gradually with depth. The length of growing season, S, is rather short at 133 d. Dissolved oxygen (DO) levels (mg L^{-1}) were near saturation (>85%) on all sampling dates.
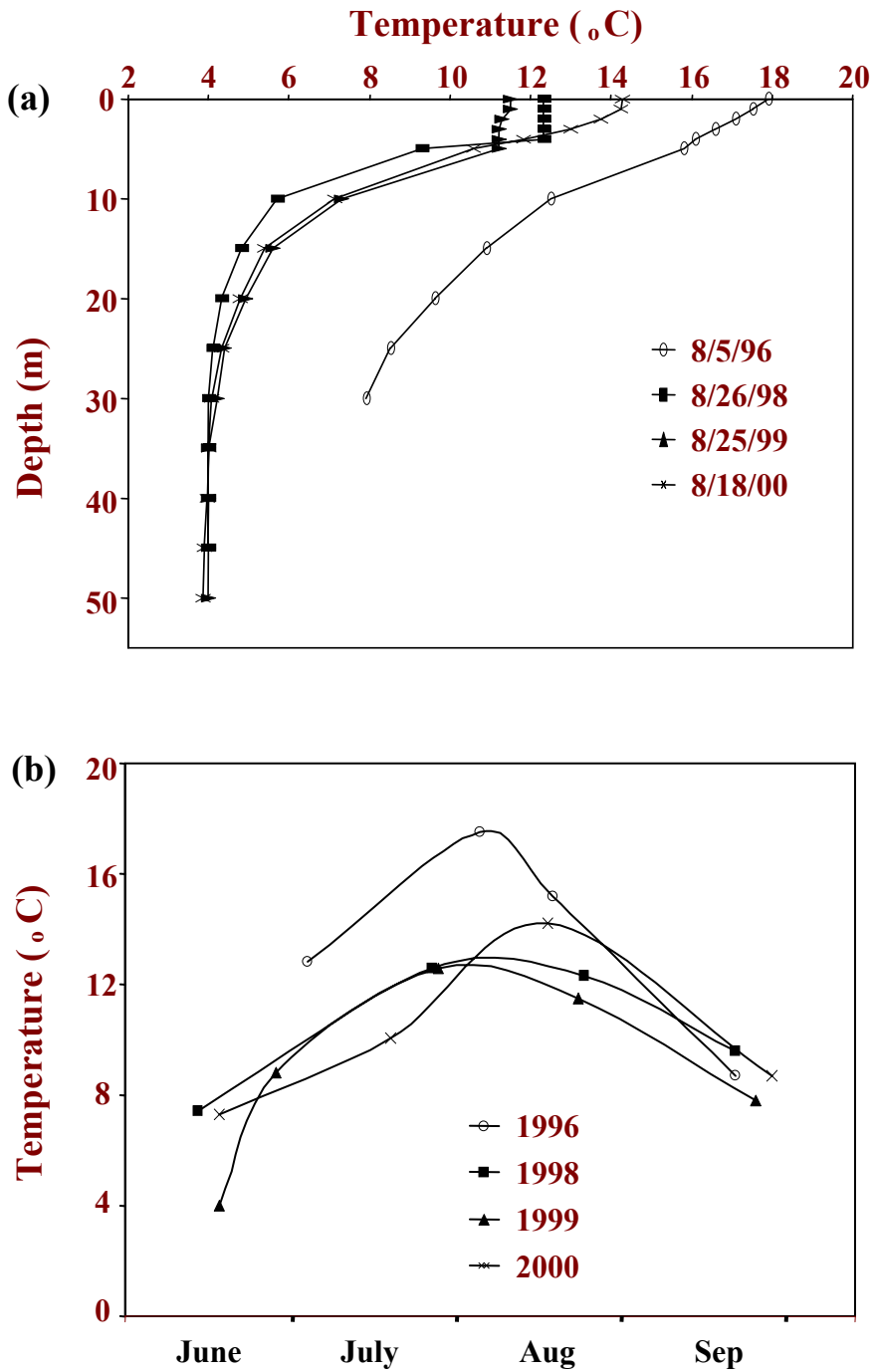
Figure 4. Vertical temperature profiles during time of maximum heat
content (a), and seasonal changes in water temperatures of the
1-m stratum (b) in Solf Lake, 1996 and 1998-2000.

Solf Lake is an extremely clear water system. Light penetration was much less variable in 2000 than in the other years. In 1999 median EZD and SD transparency were greatest (deeper), 31.7 m and 19.7 m, respectively. Median EZD ranged from 23.5 to 30.1 m (Figure 5a), and median SD transparency varied from 14.5 to 17.0 (Figure 5c) for other years. Median K_d varied from 0.145 to 0.200 m^{-1} during 1996 and 1998-2000 (Figure 5b).

Nutrients, Chemistry, and Primary Production

There was little annual or yearly variation in most measured water chemistry, nutrient concentrations, or chlorophyll parameters (Table 3, Table 4). The pH was slightly acidic (5.8) and alkalinity, a measurement of the ability of water to resist changes in pH, was very low (2.4 mg L^{-1}). Conductivity, an indirect measure of dissolved minerals, was also very low (16 μmhos cm^{-1}). As expected from measurements of light penetration and water clarity, Solf Lake exhibited very little turbidity (0.5 NTU) or color (5 Pt units). Based on average total nitrogen (47.9 μg L^{-1}), phosphorus concentrations (3.6 μg L^{-1}) and chlorophyll concentrations, Solf Lake is classified as very oligotrophic. Chlorophyll *a*, an index of algal biomass, never exceeded 0.5 μg L^{-1} and averaged only 0.23 μg L^{-1} (Table 3). Mean nutrient, chemistry, and chlorophyll *a* concentrations in Solf Lake were all lower than the means for 57 Alaskan lakes that support sockeye salmon (Table 5).

Zooplankton Assessment

Species Composition, Density, and Biomass

The zooplankton community in Solf Lake consists of two copepods, *Cyclops scutifer* and *Diaptomus kenai*, and two cladocerans, *Bosmina coregoni* and *Daphnia longiremis*. However, *D. longiremis* has not been found in any samples since 1983. *Cyclops* (Table 6, Figure 6), comprised over 50% of the population density and predominated the zooplankton population. The seasonal, mean total density fluctuated greatly among years, but was more variable before stocking (56,155 to 213,491 m^{-2}). Prior to stocking, seasonal mean densities of *Cyclops* ranged from 39,395 to 195,237 m^{-2}, whereas *Bosmina* ranged from 7,412 to 58,832 m^{-2} (Table 6). For both *Cyclops* and *Bosmina*, the mean densities decreased after stocking: *Cyclops* decreased 62% (from 86,621 to 33,146 m^{-2}) and *Bosmina* decreased 42% (from 23,439 to 13,594 m^{-2}). *Diaptomus* density increased slightly from 16,369 to 17,322 m^{-2} during stocking compared to pre-stocking. The ANOVA results suggested no significant difference (*P*=0.129) in zooplankton species density (all species) between the pre-stocking and stocking periods (Table 7). Station 2 also showed similar decreases for *Cyclops* and *Bosmina* and an increase for *Diaptomus* after stocking.

Except in 1986, *Diaptomus* was the dominant species in terms of biomass (Figure 6). Although *Diaptomus* density was less than *Cyclops*, their larger mean size (1.48 mm) contributed more biomass to the lake. Prior to stocking, the seasonal mean biomass of *Cyclops* ranged from 64 to 351 mg m^{-2}, whereas, *Bosmina* ranged from 23 to 188 mg m^{-2}. For both *Cyclops* and *Bosmina*, the mean biomass decreased after stocking as expected: *Cyclops* decreased 68% (from 147 to 47
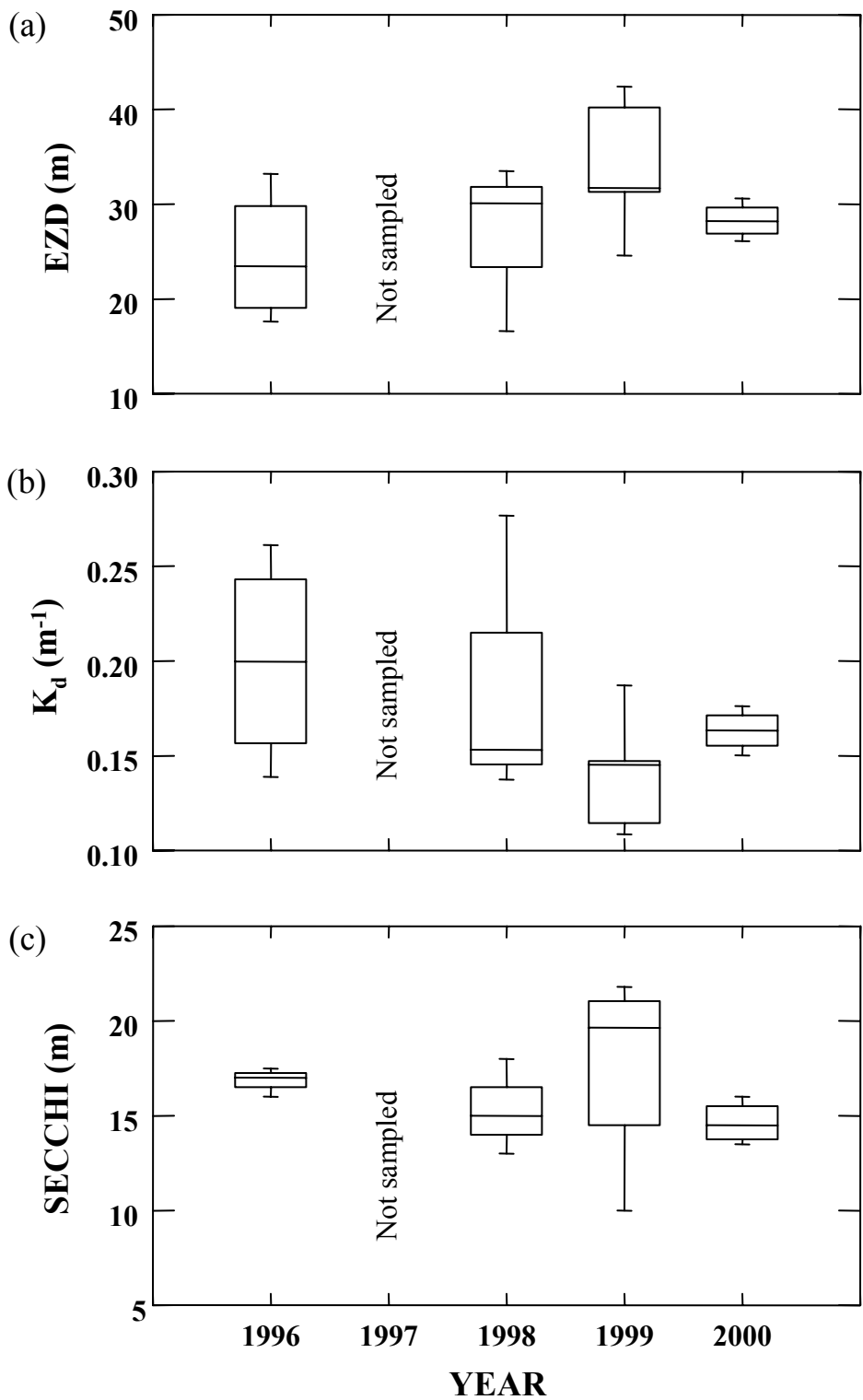
12

(a)

(b)

(c)

Figure 5. Box-plots of depth of euphotic zone depth (EZD) (a), vertical
light extinction coefficient (K_d) (b), and Secchi disk transparency
(c) in Solf Lake, 1996 and 1998-2000. Box identifies 50% of the
data, the median is the line across the box, lines outside the box
(top and bottom) are the range of the data values.

13

Table 3. Summary of water chemistry, nutrients, and chlorophyll *a* for the 1-m stratum in Solf Lake.

Parameter	Units	1982	1983	1984	1986	1996	1998	1999	2000	Mean
Conductivity	µmhos cm^{-1}	17	16	18	17	15	14	16	14	16
pH	Units	6.0	6.0	5.4	5.9	5.8	6.0	5.9	5.5	5.8
Alkalinity	mg L^{-1}	3.0	2.8	2.3	2.0	1.9	2.9	2.7	1.7	2.4
Turbidity	NTU	nd [a]	nd	0.3	0.3	0.5	0.9	0.4	0.5	0.5
Color	Pt units	nd	nd	6	4	5	7	5	4	5
Calcium	mg L^{-1}	1.2	2.1	0.9	2.6	0.8	0.7	0.7	0.7	1.1
Magnesium	mg L^{-1}	0.2	0.2	0.7	0.2	0.3	0.3	0.3	0.4	0.3
Iron	µg L^{-1}	14	12	17	11	14	13	14	12	14
Total-P	µg L^{-1}	3.2	6.5	6.0	2.9	2.3	2.3	1.3	1.8	3.6
Total filterable-P	µg L^{-1}	2.4	7.2	5.2	2.5	1.2	1.4	0.6	1.9	3.1
Filterable reactive-P	µg L^{-1}	0.5	0.6	0.9	1.0	0.6	1.4	0.3	1.2	0.8
Kjeldahl-N	µg L^{-1}	28.9	30.0	40.4	29.0	48.8	53.1	29.8	34.4	36.8
Ammonia	µg L^{-1}	5.5	1.7	5.2	3.1	5.7	4.9	6.8	11.3	5.3
Nitrate+nitrite	µg L^{-1}	21.1	6.2	8.6	10.6	14.2	6.0	11.2	13.9	11.0
Total-N	µg L^{-1}	50.0	36.2	49.0	39.6	63.1	59.1	41.0	48.2	47.9
Total-N:Total-P [b]		36:4	25:5	25:9	37:9	63:9	69:4	74:3	58:8	47:1
Reactive silicon	µg L^{-1}	800	757	845	600	825	836	877	794	797
Particulate organic carbon	µg L^{-1}	48	98	22	77	52	26	69	58	57
Chlorophyll *a*	µg L^{-1}	0.15	0.45	0.31	0.26	0.11	0.15	0.08	0.27	0.23
Phaeophytin	µg L^{-1}	0.10	0.25	0.22	0.17	0.09	0.07	0.08	0.12	0.15

[a] nd means no data available.

[b] Total-N:Total-P ratio is expressed by molecular weight.

Table 4. Summary of water chemistry, nutrients, and chlorophyll *a* for the 50 m stratum in Solf Lake.

Parameter	Units	1982	1983	1984	1986	1996	1998	1999	2000	Mean
Conductivity	mmhos cm^{-1}	18	21	18	18	17	18	18	18	18
pH	Units	5.9	6.1	5.4	5.9	5.6	6.0	5.7	5.5	5.7
Alkalinity	mg L^{-1}	2.8	2.8	3.0	2.0	1.8	2.7	2.5	2.0	2.5
Turbidity	NTU	nd [a]	nd	0.3	0.3	0.4	0.8	0.5	0.6	0.4
Color	Pt units	nd	nd	5	4	4	4	5	6	5
Calcium	mg L^{-1}	1.5	1.9	0.9	2.8	0.8	0.8	0.9	0.9	1.2
Magnesium	mg L^{-1}	0.2	0.4	0.7	0.2	0.4	0.3	0.4	0.5	0.4
Iron	mg L^{-1}	16	16	17	15	12	11	14	12	14
Total-P	mg L^{-1}	2.7	3.3	2.5	2.0	3.1	2.2	1.1	1.8	2.4
Total filterable-P	mg L^{-1}	1.8	1.8	1.3	2.0	1.1	0.7	0.5	1.9	1.4
Filterable reactive-P	mg L^{-1}	0.5	0.7	0.7	0.9	0.5	0.4	0.4	1.4	0.7
Kjeldahl-N	mg L^{-1}	17.3	25.0	35.5	23.2	44.9	44.7	28.0	31.8	31.3
Ammonia	mg L^{-1}	6.4	3.9	10.3	4.9	6.6	4.7	6.5	12.1	7.0
Nitrate+nitrite	mg L^{-1}	22.8	19.9	18.4	22.4	26.5	24.8	18.5	31.2	22.5
Total-N	mg L^{-1}	40.1	44.9	53.9	45.6	71.4	69.5	46.5	63.0	53.8
Total-N:Total-P [b]		32:7	42:4	54:9	52:3	61:3	78:9	96:5	80:8	60:8
Reactive silicon	mg L^{-1}	712	770	862	822	800	860	931	888	830
Particulate organic carbon	mg L^{-1}	53	117	10	104	14	7	36	33	48
Chlorophyll *a*	mg L^{-1}	nd	nd	nd	nd	0.05	0.11	0.04	0.36	0.14
Phaeophytin	mg L^{-1}	nd	nd	nd	nd	0.12	0.10	0.16	0.38	0.19

[a] nd means no data available.

[b] Total-N:Total-P ratio is expressed by molecular weight.

Table 5. Comparison of seasonal (May-September) mean water chemistry, nutrient
concentrations, and algal pigments in Solf Lake to 57 clear-water Alaskan lakes.

Parameter	Units	(n)	Minimum	Maximum	Mean	Solf Lake
Conductivity	μmhos cm^{-1}	657	6	173	68	16
pH	Units	657	5.4	8.9	7.2	5.8
Alkalinity	mg L^{-1}	658	1.5	85.0	21.6	2.4
Turbidity	NTU	653	0.2	5.2	0.9	0.5
Color	Pt units	642	2	27	8	5
Calcium	mg L^{-1}	655	0.7	33.2	7.9	1.1
Magnesium	mg L^{-1}	602	0.2	11.6	1.4	0.3
Iron	μg L^{-1}	628	3	457	44	14
Total-P	μg L^{-1}	652	1.0	36.6	6.8	3.6
Total filterable-P	μg L^{-1}	642	0.1	23.1	3.7	3.1
Filterable reactive-P	μg L^{-1}	647	0.2	21.3	2.5	0.8
Kjeldahl-N	μg L^{-1}	659	11	431	105	37
Ammonia	μg L^{-1}	598	1.0	118.1	8.4	5.3
Nitrate+nitrite	μg L^{-1}	613	1.0	634	100	11
Reactive silicon	μg L^{-1}	642	4	6,809	1,722	797
Chlorophyll *a*	μg L^{-1}	612	0.02	18.72	1.23	0.23
Phaeophytin	μg L^{-1}	610	0.01	10.07	0.60	0.15

Table 6. Mean macrozooplankton density (Nr. m^{-2}) by genus for stations 1 and 2, and for both stations combined.

Station - 1

Year	Diaptomus	Cyclops	Bosmina	Daphnia	Total
1982	17,546	68,569	11,766	663	98,544
1983	24,962	41,716	58,832	495	126,005
1984	9,348	39,395	7,412	np [a]	56,155
1986	3,141	195,237	15,113	np	213,491
Pre- 1996	26,847	88,190	24,070	np	139,107
Stock- 1998	29,440	25,913	11,112	np	66,465
1999	9,044	29,894	5,732	np	44,671
2000	13,482	43,631	23,939	np	81,052
Pre-stocking mean	16,369	86,621	23,439	579	126,660
Stocking mean	17,322	33,146	13,594		64,063

Station - 2

Year	Diaptomus	Cyclops	Bosmina	Daphnia	Total
1996	29,525	88,470	48,343	np	166,338
1998	53,573	49,166	21,860	np	124,599
1999	10,021	29,321	4,034	np	43,376
2000	6,316	42,941	28,025	np	77,282
Pre-stocking mean	29,525	88,470	48,343		166,338
Stocking mean	23,303	40,476	17,973		81,752

Stations 1 and 2 combined

Year	Diaptomus	Cyclops	Bosmina	Daphnia	Total
1982	17,546	68,569	11,766	663	98,544
1983	24,962	41,716	58,832	495	126,005
1984	9,348	39,395	7,412	np	56,155
1986	3,141	195,237	15,113	np	213,491
1996	28,186	88,330	36,207	np	152,723
1998	41,507	37,540	16,486	np	95,532
1999	9,533	29,607	4,883	np	44,023
2000	9,899	43,286	25,982	np	79,167
Pre-stocking mean	18,561	86,930	27,589	579	133,273
Stocking mean	20,313	36,811	15,784		72,907

[a] Species not present.
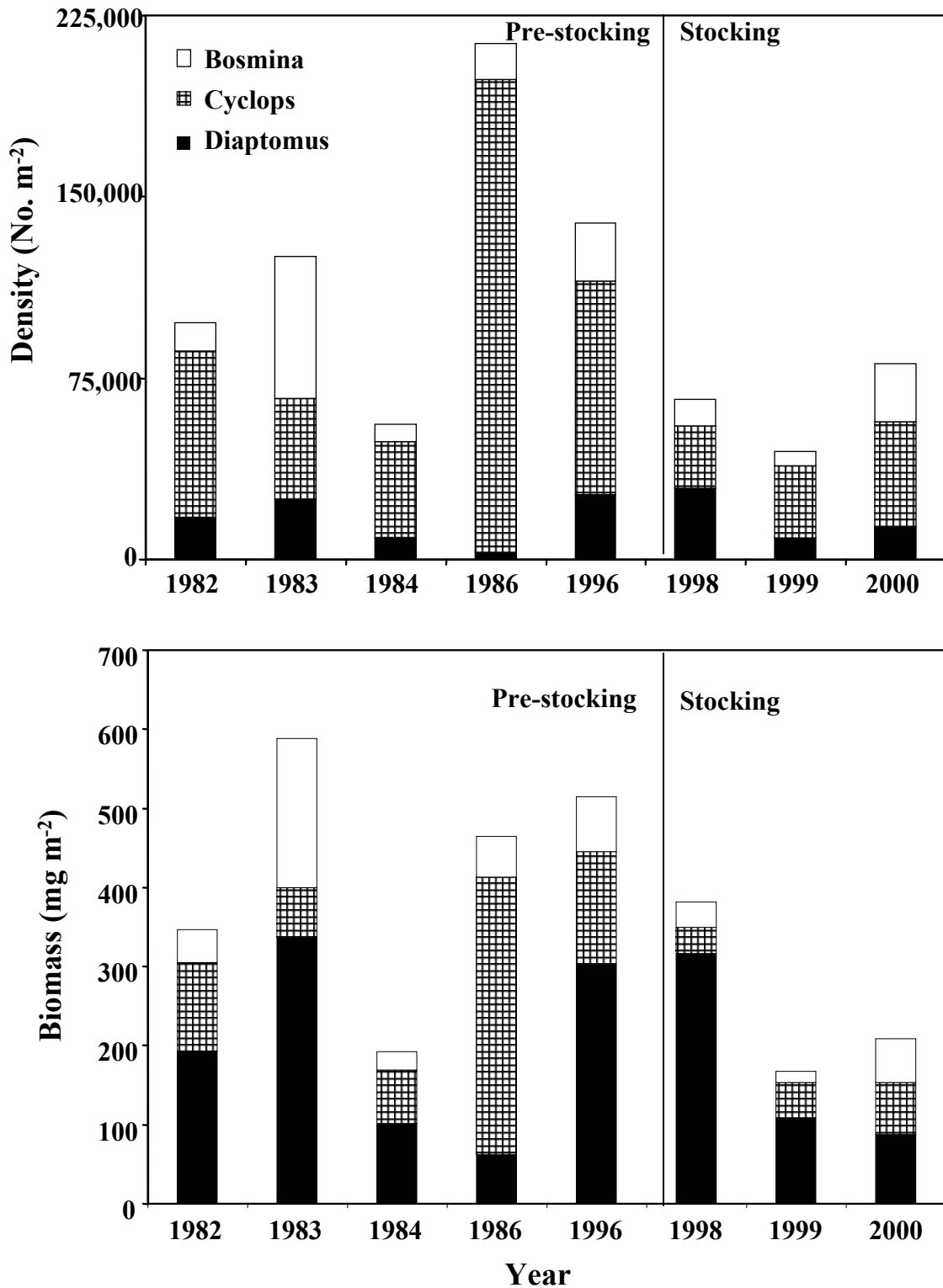
Figure 6. Zooplankton abundance (top), and biomass (bottom), by genus in Solf Lake, 1982-1984, 1986, 1996, and 1998-2000.

Table 7. Results of ANOVA to test for differences before and during stocking in macrozooplankton density, biomass, and mean length. *P*-values less than 0.05 are significant.

Variable	Mean Pre-stocking	Stocking	F-Ratio	*P*-Value
Density (Nr. m^{-2})				
Cyclops	86,621	33,146	1.944	0.213
Diaptomus	16,369	17,322	0.016	0.904
Bosmina	23,439	13,594	0.577	0.476
Total	126,429	64,062	3.089	0.129
Biomass (mg m^{-2})				
Cyclops	147.4	53.0	1.741	0.235
Diaptomus	198.6	161.7	0.166	0.698
Bosmina	74.8	34.7	1.003	0.355
Total	420.8	249.3	2.713	0.151
Length (mm)				
Cyclops	0.696	0.643	9.792	**0.020**
Diaptomus	1.482	1.320	2.284	0.181
Bosmina	0.578	0.527	8.858	**0.025**

mg m^{-2}) and *Bosmina* decreased 55% (from 75 to 34 mg m^{-2}) (Table 8). *Diaptomus* biomass also decreased 16% during stocking. Results of ANOVA suggested no significant difference (*P*=0.151) in biomass (all species) between the pre-stocking and stocking periods (Table 7). Station 2 also showed similar decreases in biomass during the stocking period, with *Diaptomus* decreasing over 1.7 fold. However, when the data for both stations were combined, there was a small increase in *Diaptomus* biomass, from 214 to 221 mg m^{-2} during the stocking period, but this 7 mg m^{-2} increase was not statistically significant (*P*>0.05, Table 7).

Zooplankton mean sizes decreased slightly after fry stocking for all species except for *Bosmina* at station 2, which showed a slight increase (Table 9). *Diaptomus* was the largest species in Solf Lake and size ranged from 1.14 to 1.71 mm, with mean sizes of 1.48 mm pre-stocking and 1.32 mm during stocking. Mean sizes for all species fluctuated yearly, and both *Diaptomus* and *Cyclops* sizes were largest in 1986 (Figure 7). Results of ANOVA indicated that the mean sizes of *Cyclops* (*P*=0.020) and *Bosmina* (*P*=0.025) were smaller during stocking compared to before stocking (Table 7).

Fisheries Assessment

Smolt and Fry Abundance and Size

Between 2 May and 26 June 1999, only 248 sockeye salmon smolt and 45 Dolly varden were enumerated. Peak emigration occurred on 6 June (no smolt left before 5 June), when 189 smolt were enumerated (Table 10). The net blocking the northwest outlet, and the live-box and later the inclined-plane trap at the northeast outlet, did not allow uncounted fish passage during the enumeration project. Because of the small number of emigrating smolt, we sampled only 16 smolt for age and size. The mean smolt size was 134.7 mm (range 122-153 mm) and 22.9 g (range 16.1-30.5 g).

Results of the 27 September 1999 hydroacoustic survey showed very few fish rearing in the lake. Only three targets were recorded on the chart paper for all 12 transects and no fry were captured in the tow net. Results from the 15 June 2000 hydroacoustic survey were similar to the 1999 survey in that only 19 targets were recorded. Ten echoes were from one fish with an average target strength (TS) of -43.7 dB. The remaining 9 echoes were from another fish and the average TS was -55.8 dB, which indicated this fish was a fry. During the 19 July 2000 survey there were no targets recorded. Because we saw essentially no fish acoustically on either survey in 2000, we did not conduct tow netting in 2000.

Table 8. Mean macrozooplankton biomass (mg m^{-2}) by genus for stations 1 and 2, and for both stations combined.

Station - 1

	Year	*Diaptomus*	*Cyclops*	*Bosmina*	*Daphnia*	Total
	1982	193	112	41	1	347
	1983	336	64	188	1	589
	1984	102	67	23	np [a]	192
	1986	62	351	51	np	464
Pre-	1996	300	143	71	np	514
Stock-	1998	313	32	33	np	378
	1999	108	44	15	np	166
	2000	83	64	56	np	203
Pre-stocking mean		199	147	75		421
Stocking mean		168	47	34		249

Station - 2

Year	*Diaptomus*	*Cyclops*	*Bosmina*	*Daphnia*	Total
1996	458	126	129	np	714
1998	630	66	73	np	769
1999	125	46	12	np	182
2000	70	63	77	np	210
Pre-stocking mean	458	126	129		714
Stocking mean	275	59	54		387

Station 1 and 2 combined

Year	*Diaptomus*	*Cyclops*	*Bosmina*	*Daphnia*	Total
1982	193	112	41	1	347
1983	336	64	188	1	589
1984	102	67	23	0	192
1986	62	351	51	0	464
1996	379	135	100	np	614
1998	471	49	53	np	574
1999	116	45	13	np	174
2000	77	64	66	np	206
Pre-stocking mean	242	144	84		470
Stocking mean	221	53	44		318

[a] Species not present.

Table 9. Mean macrozooplankton size (mm) by genus for stations 1 and 2.

	Year	*Diaptomus*	*Cyclops*	*Bosmina*	*Daphnia*
		Station - 1			
	1982	1.40	0.69	0.60	1.10
	1983	1.50	0.67	0.58	0.52
	1984	1.39	0.71	0.57	np [a]
	1986	1.72	0.72	0.59	np
Pre-	1996	1.41	0.69	0.55	np
Stock-	1998	1.38	0.61	0.56	np
	1999	1.44	0.66	0.52	np
	2000	1.14	0.66	0.51	np
Pre-stocking mean		1.48	0.70	0.58	0.81
Stocking mean		1.32	0.64	0.53	
		Station - 2			
	1996	1.58	0.65	0.53	np
	1998	1.43	0.63	0.59	np
	1999	1.46	0.68	0.55	np
	2000	1.40	0.66	0.54	np
Pre-stocking mean		1.58	0.65	0.53	
Stocking mean		1.43	0.66	0.56	

[a] Species not present.

Diaptomus

Pre-stocking   Stocking

Cyclops

Pre-stocking   Stocking

Bosmina

Pre-stocking   Stocking

Year
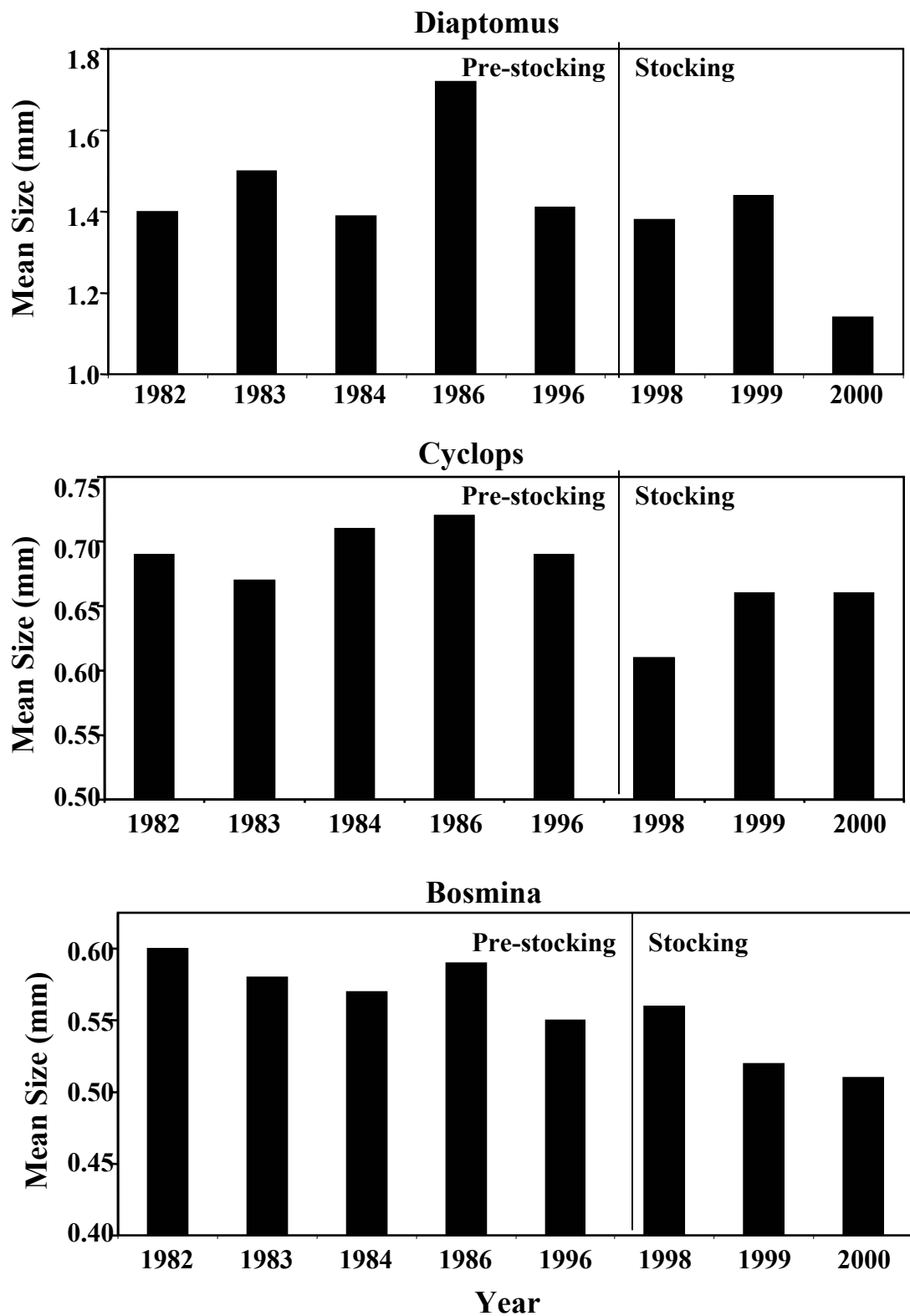
Figure 7. Zooplankton mean body size, by genus in Solf Lake, 1982-1984, 1986, 1996, and 1998-2000.

23

Table 10. Daily and cumulative counts of sockeye
sockeye smolt emigrating Solf Lake, 1999.

| Date [a] | Sockeye salmon | | Other |
	daily	cumm.	DV [b]
5/8			1
5/9			2
5/10			1
5/11			1
5/14			1
5/15			2
5/16			1
5/17			1
5/18			
5/19			1
5/26			3
5/27			1
5/28			1
5/29			2
5/30			3
5/31			1
6/1			9
6/5	23	23	
6/6	189	212	4
6/7	13	225	1
6/8	16	241	3
6/9		241	
6/10		241	
6/11		241	
6/12		241	
6/13		241	2
6/14		241	
6/15		241	
6/16		241	
6/17	2	243	
6/18	1	244	
6/19		244	
6/20		244	
6/21		244	
6/22		244	
6/23		244	
6/24		244	
6/25	1	245	1
6/26	3	248	3
Total		248	45

[a] Multiple dates with no fish counts were ommited.
[b] DV is Dolly varden trout (*Salvelinus malma*).

DISCUSSION

Zooplankton and Limnology Relative to Sockeye Salmon Stocking

High fry mortality can occur if insufficient zooplankton, either in terms of abundance or species composition, are available (Foerster 1968), or if stocking occurs before spring zooplankton blooms. In June 1998 and 1999, *Cyclops* and *Bosmina* densities were low in Solf Lake at the time of stocking, as was the case in June 2000 for *Bosmina* (Figure 8). Changes in zooplankton abundance, composition and size distribution from high fry densities have been related to overgrazing (Kyle et al. 1998). Schmidt et al. (1994) argued that Cyclops in glacially influenced Skilak Lake underwent exaggerated diel vertical migration in response to increased predation by sockeye salmon fry resulting from large escapements. The copepods *Cyclops* and *Diaptomus* are more evasive and can migrate deeper in the water column than cladocerans such as *Bosmina* (O'Brien 1979). Nilsson (1972) also noted that large zooplankton species are reduced or eliminated by predation from the introduction of planktivorous fish. Therefore, in Solf Lake we might expect that the impacts of stocking would be greater on cladoceran populations than copepods. However, we found little evidence of excessive planktivory or grazing by rearing sockeye salmon juveniles in Solf Lake (Table 7). Neither density nor biomass of any species differed significantly before and during stocking. Nonetheless, there are indications of planktivory because the mean lengths were smaller during stocking (Table 9, Figure 7). The decrease in body sizes of *Cyclops* and *Bosmina* during stocking is considered very small and probably not biologically meaningful. Both *Cyclops* and *Bosmina*, with mean body sizes less than one half the size of *Diaptomus*, were the preferred prey as shown by the decreased body sizes and biomass (a 3-fold biomass decrease for *Cyclops* and over 2-fold for *Bosmina*). Koenings and Burkett (1987) found that sockeye salmon fry preferred food in a size range of 0.40 to 1.00 mm and that *Cyclops* was not a preferred prey when other species are available, even though they were in the preferred size range and densities were high.

The *Diaptomus* in Solf Lake exhibited a red pigmentation, which probably makes them highly visible to rearing sockeye salmon juveniles, and Solf Lake is extremely clear so we expected to see a substantial decrease in *Diaptomus* abundance and biomass. Based on comparisons of density and biomass before and during stocking, we did not see strong evidence of excessive grazing (our statistical analyses showed no differences). Also, only two other Alaskan lakes are known to contain pigmented populations of *Diaptomus* (J. M. Edmundson, ADF&G, personal communication). The red coloration may be caused by carotenoids from the algal diet of zooplankton, and possibly acts as energy storage and protection from harmful ultra-violet radiation (UV) (Ringelberg 1980). Hairston (1976, 1978) conducted experiments on pigmented and translucent *Diaptomus* and found the pigmented morphs had higher survival in both low and high light intensity, and they were found in greater concentrations near the surface. We suggest the high water clarity coupled with low predation rates on the zooplankton may be the environmental or ecological causes for evolution of the different (red) form of *Diaptomus* in Solf Lake.

Kyle (1996) found mixed results from the stocking of sockeye salmon fry in small, barren lakes (~ 2 km^2) in Alaska. His study showed that compared to pre-stocking, the average standing crop
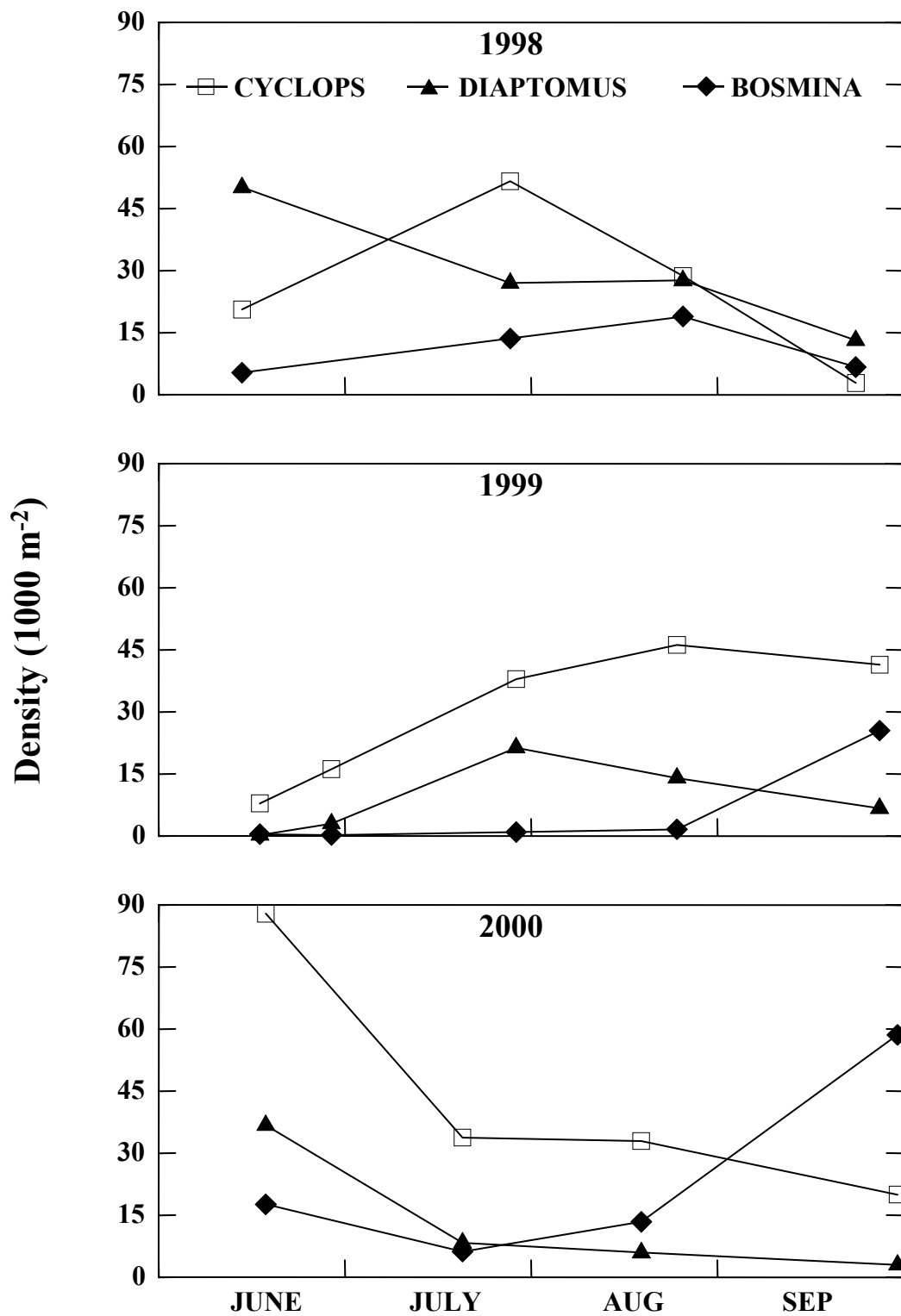
Figure 8. Seasonal changes in zooplankton density, by genus in Solf Lake, 1998-2000.

of zooplankton increased slightly in some lakes whereas in others there was up to a 500% decrease. Edmundson et al. (1993) found similar results when two small, barren lakes were stocked in Prince William Sound, Alaska. For example, after two years of stocking in Pass Lake (0.5 km^2) the total zooplankton biomass decreased by 92%, and the zooplankton community structure changed dramatically; *Diaptomus*, *Daphnia* and *Holopedium* were all but eliminated. In Esther Passage Lake (0.2 km^2), the zooplankton community did not recover from excessive grazing even though stocking was curtailed and the lake fertilized. In Virginia Lake (2.6 km^2), a clear barren lake in Southeast Alaska, fry to smolt (threshold size) survival from stocking was only 3.7% the first year, and was partially attributed to insufficient forage at time of stocking and a high stocking rate (Edmundson et al. 1991). Leisure Lake (1.1 km^2), a clear barren lake in Kachemak Bay, Alaska, was stocked annually for three years and fry to age-1 smolt (threshold size) survival declined from 21% the first year to 2% by the third year. Stocking at carrying capacity decreased zooplankton densities and biomass dramatically and shifted the size distribution from large-bodied *Daphnia* to small *Bosmina* (Koenings and Kyle 1997). DeCino (1992) found 90% mortality of stocked sockeye salmon fry after six weeks in a small, stained oligotrophic lake in Southeast Alaska. However, stocking of larger, deeper systems have been successful and have not negatively impacted the zooplankton community, because they may offer zooplankton more refugia from visually attuned predators such as sockeye salmon fry. In Spiridon Lake (9.2 km^2) on Kodiak Island, fry to smolt survival averaged 29% over three years, and impacts to the forage base were minimal (Honnold 1997).

Solf Lake is very oligotrophic based on its low nutrient and chlorophyll concentrations (Tables 3 and 4). Compared to 57 other sockeye salmon lakes, mean water chemistry values, nutrient concentrations, and algal pigment levels for Solf Lake were much lower (Table 5). Small, oligotrophic lakes can be susceptible to changes in water chemistry (e.g., pH), because they have small amounts of dissolved minerals (e.g., alkalinity), that act as buffers to inhibit changes. When nutrient concentrations, chemical concentrations, or both are low (like nitrogen and phosphorus), productivity can be limited (Gilbert and Rich 1927; Schindler 1978). This lake is also very clear (mean SD depth 16.1 m) compared to 44 other clear water Alaskan lakes, with a mean SD depth of 7.2 m and ranges of 2.3-14.7 m (Koenings and Edmundson 1991). SD depth has been used as an index of water quality (Cooke et al. 1993) and for lake trophic state classification (Carlson 1977). In clear lakes with very little yellow (organic) color, SD transparency was inversely proportional to chlorophyll concentrations (LaPerriere and Edmundson 2000). Algal biomass averaged 0.23 µg L^{-1} (Table 3), which is less than 20% of the mean value (1.23 µg L^{-1}) for the other clear water Alaskan nursery lakes (Table 5). As such, the deep SD measurements further illustrate the oligotrophic nature (deficiency of nutrients and algal concentrations) of Solf Lake.

Subsurface water temperatures in Solf Lake (1 m) were cold at the time of stocking, 7° C in 1998 and 2000, and 4 ^{o}C in 1999 (Figure 4b), which could further limit fry growth and survival. Brett (1971) found growth rates of age-0 sockeye salmon were proportional to temperature when food was in excess and at lower food densities the temperature was lower for maximum growth, with 11.5^o C the peak temperature for growth efficiency conversion. Edmundson and Mazumder (2001) related zooplankton and temperature variables in Alaskan lakes to sockeye salmon smolt size and found that zooplankton biomass explained 52%, and seasonal mean water column temperature (T_s) explained 20% of the variation in smolt length, while length of the growing

season (S) was not significantly related to smolt size. Peltz and Koenings (1989) found that zooplankton biomass explained 59-77% of the variation in age-1 and age-2 smolt numbers, and 67% of the variation in age-1 smolt weight was explained by mean rearing temperature (sub-optimal rearing temperatures). Although the 5 m depth temperatures (8° C) were within a degree of the optimum temperature for growth during 1998 and 2000, temperatures at 10 m ($\sim6^o$ C) and deeper were much colder (Figure 4a). Based on thermal characteristics (means) of 29 clear water Alaskan lakes (Edmundson and Mazumder 2002), Solf Lake has a shorter S (133 d vs. 171 d), and H_i is projected 23 days later (d 157 vs. d 134) (Table 4). Although the projected day of H_m and $T_{max,}$ and θ_s were similar; (H_m d 223 vs. d 219), (T_{max} 13.7 vs. 13.5 ^{o}C), and (θ_s 10.4 vs. 11.4 k-cal cm^{-2}) respectively.

The sockeye salmon fry stocking density in Solf Lake was low compared to current carrying capacity models for sockeye salmon. The euphotic volume (EV) model of 115,000 fry per EV unit (10^6 m^3 per unit) predicts threshold size smolt (23,000 smolt at 60 mm and 2.0 g, 20% fry-to-smolt survival) production at rearing capacity (Koenings and Burkett 1987). However, this model is highly influenced by a few lakes with large surface areas and is probably not applicable for Solf Lake (Edmundson and Carlson 1999). Unlike the EV model, the EZD model [EZD (m) $\times 0.095$ = Ln SB (kg km^{-2})] is on based euphotic zone depth alone, and thus is a better proxy for primary productivity (Edmundson and Carlson 1999). The zooplankton biomass (ZB) model [ZB (mg m^{-2}) $\times 2.11$ = SB (kg km^{-2})] assumes that when lakes are at rearing capacity (food resources are limited) SB is a function of ZB (Koenings and Kyle 1997). The predicted smolt abundance in Solf Lake using the EV, EZD, and ZB models are shown below. The lower and upper smolt numbers were calculated using 4.5 g, considered the optimal size, and 2.0 g, considered the threshold size for sockeye salmon smolt (Koenings and Burkett 1987; Koenings and Kyle 1997). To estimate carrying capacity in terms of fry, we back calculated from predicted smolt abundance using an assumed fry to smolt survival of 20% for threshold size smolt numbers.

Model	Mean, units	Fry number (x 10^3)	Smolt number (x 10^3)
EV	18.4, 10^6 m^3	2,116	188 - 423
EZD	30.3, m	5,870	575 - 1,174
ZB	318, mg m^{-2}	1,022	91 - 204

Solf Lake was stocked well below carrying capacity based on the predicted results of the EV, EZD, and ZB models predictions. For example, the yearly stocking rate of 110,000 fry is approximately 10% of the estimated number of fry that a lake with a planktivorous fish population would support based on the ZB model. The mean stocking density in Solf Lake (6,200 EV^{-1} unit or 0.19 m^{-2}) was also low compared to the mean of 13 other barren lakes in Alaska that have been stocked (49,750 EV^{-1} unit or 0.51 m^{-2}) (Table 11). We do not believe the fry emigrated as age-0 smolts because most of the fry reared for less than a month, and there is no estuary at the creek mouth where lower salinity water could allow fry to survive and emigrate later as age-0 smolt. However, migration of young-of-the year sockeye salmon juveniles (age-0)

Table 11. Morphometric and sockeye salmon fry stocking information (means) for Solf Lake compared to 13 barren lakes in Alaska (data reproduced from Kyle 1996).

Lake	Geographical region [c]	S.A. (km^2)	Max. depth (m)	EZD [a] (m)	EV [b] (m^3 x 10^6)	Years	Stocking level No. (x 10^3)	No. EV^{-1}	No. m^{-2}
Hidden	Kodiak	1.9	49	12.5	24	2	427	29,300	0.23
Crescent	Kodiak	0.6	35	13.5	8	2	301	36,950	0.51
Waterfall	Kodiak	1.0	18	9	9	2	349	37,650	0.35
Spiridon	Kodiak	9.2	82	32.3	294.3	4	2,503	8,950	0.27
Pass	PWS/Gulf	0.5	31	11	5.3	3	432	74,300	0.87
Ester Pass	PWS/Gulf	0.2	27	7	1.3	3	144	110,000	0.73
Port Dick	PWS/Gulf	1.0	45	34	nd [d]	3	452	6,400	0.45
Bruin	Cook Inlet	0.9	20	5	5	3	333	74,100	0.37
Kirschner	Cook Inlet	1.3	37	24.6	31.8	7	377	10,080	0.29
Hazel	Cook Inlet	0.9	26	16.8	15.5	5	1,057	79,725	1.17
Ursus	Cook Inlet	0.7	22	9	6	2	250	39,700	0.36
Upper Paint	Cook Inlet	1.0	37	26.4	26.4	7	729	26,440	0.73
Sweetheart	Southeast	4.9	155	13.3	66.3	3	1,514	113,167	0.31
Mean 13 Lakes [e]				16.5	41.1		682	49,751	0.51
Solf	PWS/Gulf	0.6	96	26.7	16.3	1998	110	6,745	0.18
				34.0	20.7	1999	106	5,104	0.17
				28.3	17.2	2000	117	6,760	0.19
						2001	116		0.19
Mean				30.3	18.4		112.1	6,203	0.18

[a] EZD (Euphotic zone depth).
[b] EV (Euphotic volume) = EZD (m) x surface area (m^2)
[c] PWS/Gulf (Prince William Sound - Gulf of Alaska)
[d] No data.
[e] Mean values are mean of displayed data, not all data for all years.

have been documented in some other systems. Age-0 smolt estimates in Chelatna Lake, Alaska, ranged from 1-62% (Fandrei 1995), and in Bear Lake near Seward, Alaska, emigrations for age-0 smolt have been as high as 98% (Hetrick and Prochazka 1998).

However, using the bioenergetic model of Beauchamp et al. (1989) with the computer program developed by Hewett and Johnson (1987) it is possible that the fry could have achieved minimal threshold size (1.5-2.0 g) in one month. Based on these threshold weights and the rearing temperature regimes available, the fry would have to eat at 54-56% of maximum consumption possible (C_{max}) to achieve 1.5 g, and 66-70% C_{max} for 2.0 g (Bob DeCino ADF&G CF, Pers. Comm). In running the bioenergetic program, we made several assumptions as we did not have diet information or final (1 month after stocking) fry weights: 1) fry reared in the upper 20 m of the water column, and 2) diet was composed of 55% *Cyclops* and 45% *Bosmina* by biomass, and *Diaptomus* were unavailable because of their large size (1.48 mm) in relation to the small size of the fry. The final fry weights of 1.5 and 2.0 g, at the end of lake rearing (1 month), were entered into the program to derive the proportion C_{max}.

We believe the fry left the system, based on visual observations of fry schooling at both outlets in 1999 and 2000 shortly after planting. Our assumptions are also supported by the 2000 hydroacoustic survey, conducted a month after stocking and very few targets were recorded. Also, the flow control structure at the inlet of the channeled stream was opened in 2000, to flush debris from previous blasting in the channel: several days after fry stocking, the stop logs were removed and the outlet remained open for approximately one week. The majority of fry could have emigrated, or have been flushed out during this period. The few smolt that emigrated Solf Lake during the spring of 1999 were very large and robust (mean 23 g), indicating there was surplus forage and little competition during the 1998-1999 rearing period.

Conclusions and Recommendations

Based on the 1999 smolt enumeration program and the 1999 and 2000 hydroacoustic surveys, the sockeye salmon fry stocked into Solf Lake appear to have either emigrated from the lake shortly after planting or died. We believe most fry emigrated the system, based on fry captures in the smolt trap in 1999, and observations of fry schooling at both outlets in 1999 and 2000 on the days of stocking. In 1999, on site crew members did not observe smolt schooling at either outlet during either day or night hours throughout the smolt season, which also indicated that few fry overwintered in the lake.

There are several possible reasons why the fry are not remaining in the lake over winter: 1) low forage base at the time of stocking (Figure 8), 2) sub-optimal rearing temperatures at the time of stocking (Figure 4b), and finally 3) late onset of spring and short growing season, caused in part by the lake's geographical orientation. The lake is shaded by steep mountains on the east (427 m height), south (722 m) and west (625 m) sides. This probably reduces solar insolation, and could lower water column temperatures and reduce the length of the growing season (Nelson 1958; France 1992; McConnell et al. 1977).

If a continuation of the stocking program is desired, we recommend continued monitoring of the forage base (zooplankton) to assess changes in density, biomass, and species composition. This will help us to balance fry stocking levels with available forage, and minimize negative impacts on the food web. Estimating adult returns to evaluate the success of stocking will not allow us to separate freshwater from marine mortality, and 4-6 years will pass before results of the stocking program will be known. We recommend that stocking be delayed for two weeks beyond dates stocked in past years based on the late onset of spring and associated low water temperatures, and low spring forage base in Solf Lake. Holding fry in net pens near an inlet stream, for a week before release into the lake may also decrease fry mortality and strengthen imprinting. This was attempted in 2001. However, the fry were crowded into a small pen ($>13,000$ fry m^{-3}), which resulted in some mortality and stressed the fish. Consequently, the fry were released after holding them for only three days. Another option for stocking Solf Lake is to release fry late in the fall.

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